REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

| 1. AGENCY USE ONLY (Leave Blank) | 2. REPORT DATE   10/31/03 | 3. REPORT TYPE AND DATES COVERED
Peer reviewed reprint |
|---|---|---|

4. TITLE AND SUBTITLE
Shot Noise in Negative-Differential-Conductance Devices

5. FUNDING NUMBERS
DAAD 19-99-1-0270
40070-PH

6. AUTHOR(S)
W. Song, E. E. Mendez, V. V. Kuznetsov, and B. Nielsen

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
State University of New York at Stony Brook

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

40070.9 - PH

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

(See reprint's abstract)

14. SUBJECT TERMS
Semiconductor Heterostructures; Shot Noise
Electronic Transport in Semiconductors; Tunneling; Resonant Tunneling

15. NUMBER OF PAGES

3

16. PRICE CODE

| 17. SECURITY CLASSIFICATION OR REPORT
UNCLASSIFIED | 18. SECURITY CLASSIFICATION ON THIS PAGE
UNCLASSIFIED | 19. SECURITY CLASSIFICATION OF ABSTRACT
UNCLASSIFIED | 20. LIMITATION OF ABSTRACT
UL |
|---|---|---|---|

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

Shot noise in negative-differential-conductance devices

W. Song, E. E. Mendez,[a] V. Kuznetsov, and B. Nielsen
Department of Physics and Astronomy, State University of New York at Stony Brook, Stony Brook, New York 11794-3800

We have compared the shot-noise properties at $T = 4.2$ K of a double-barrier resonant-tunneling diode and a superlattice tunnel diode, both of which exhibit negative differential-conductance (NDC) in their current–voltage characteristics. While the noise spectral density of the former device was greatly enhanced over the Poissonian value of $2eI$ in the NDC region, that of the latter device remained $2eI$. This result implies that charge accumulation, not system instability, is responsible for shot-noise enhancement in NDC devices. © *2003 American Institute of Physics.*
[DOI: 10.1063/1.1558953]

To gain a deep insight on the transport mechanisms of an electronic device it is sometimes essential to measure its shot noise. Then, the noise becomes the signal, paraphrasing Landauer.[1] The work described here illustrates dramatically this point, by comparing two types of semiconductor devices (a double-barrier resonant tunneling diode and a single-barrier tunneling diode with electrodes made out of doped superlattices) that exhibit similar nonlinear current–voltage ($I-V$) characteristics and yet show very different shot-noise behavior.

In a double-barrier resonant tunneling diode, the current increases linearly with voltage once the first confined state in the well between the barriers is aligned in energy with the Fermi energy of the emitter electrode. As a consequence of parallel (to the heterostructure's interfaces) momentum conservation, the current drops abruptly when the confined state falls in energy below the conduction band of that electrode. It is this negative differential conductance (NDC) and the concomitant instability of the system that is attractive for high-frequency oscillators and even digital electronics.[2]

The shot-noise properties of this device are well established both experimentally[3–6] and theoretically.[5,7,8] The noise spectral density, S, is proportional to the current I, $S = 2eFI$, where e is the electronic charge and F is the so-called Fano factor. In the linear-current regime F is smaller than one whereas in the NDC region it is larger than one, indicating negative and positive correlations in the electronic motion, respectively. In the double-barrier diode, the reduction of shot noise to a value below that of a Poissonian distribution ($S = 2eI$) is a consequence of charge accumulation in the quantum well during the tunneling process.[7,8] The enhancement has been explained in terms of the additional large potential fluctuations when the diode is in the NDC region.[5–7]

It has been pointed out by Blanter and Büttiker that, in general, system instability rather than charge accumulation, may be the necessary condition for shot noise enhancement,[8] but double-barrier diodes are not suitable to explore that suggestion, since instability (or NDC) goes hand in hand with charge accumulation. Instead, we have measured the $I-V$

characteristics and noise properties of a semiconductor diode that shows NDC behavior similar to that of a resonant-tunneling diode but in which charge accumulation does not occur.

The device, which we call *superlattice tunnel diode* and is shown in Fig. 1, consists of a single potential barrier between two identical electrodes, each formed by a doped superlattice.[9,10] For energies below that of the single-barrier height, each superlattice has two minibands separated by a one-dimensional energy gap (or pseudogap); only the ground-state miniband is (partially) occupied. On the application of a bias V, tunnel current flows between the first minibands of the electrodes, as long as eV is smaller than the miniband width, Δ. Initially, the current increases with V, but above a certain voltage (which depends on the level of occupation of the miniband) the current reaches a maximum value and then starts to decrease. When the bias exceeds the critical voltage Δ/e, at low temperature, the pseudogap be-
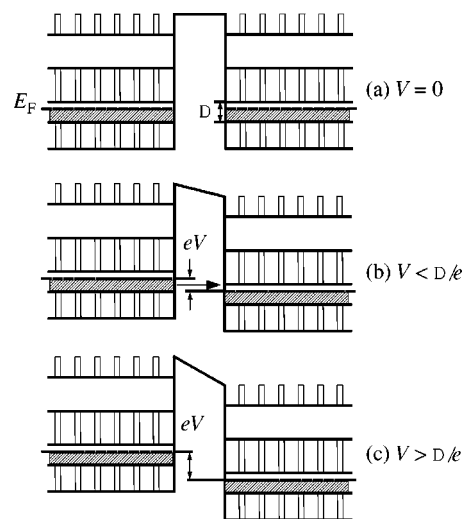

FIG. 1. Energy profile of a superlattice tunnel diode, consisting of a wide potential barrier separating two identical, doped superlattices that act as electrodes. In equilibrium, (a), the minibands of both superlattices are aligned in energy. When a bias, V, is applied between the electrodes, (b) the bands are misaligned and electrons tunnel through the barrier. If the bias exceeds the value Δ/e, (c) band misalignment is complete and the pseudogap between the first two minibands in the collector electrode prevents tunneling.
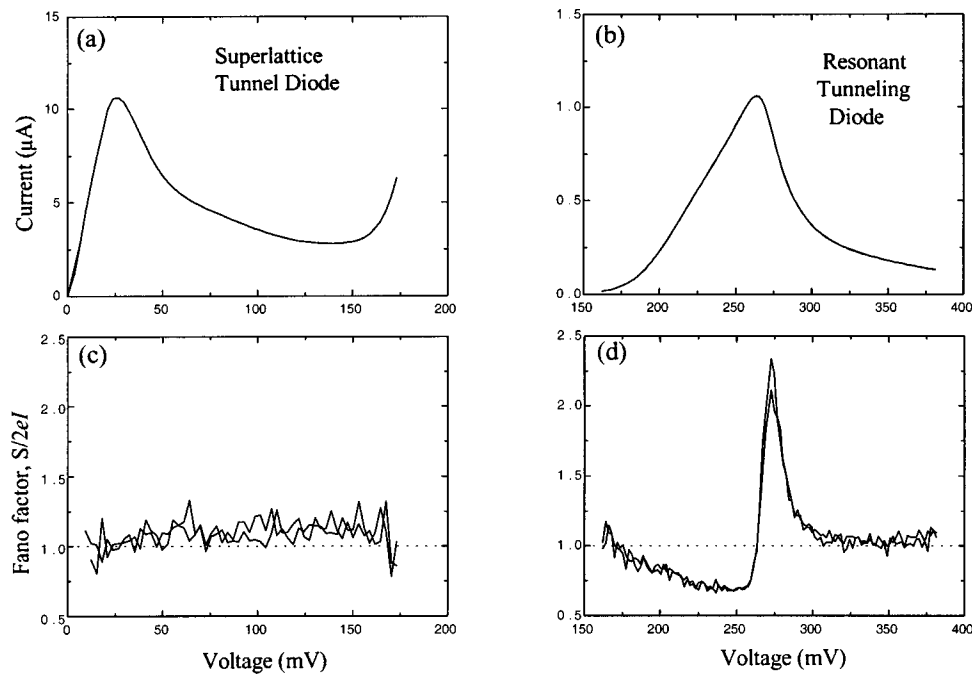
[a] Electronic mail: emendez@notes.cc.sunysb.edu

1568

FIG. 2. (a) Current–voltage characteristic, at $T = 4.2$ K, for a superlattice tunnel diode with an undoped 102 Å $Ga_{0.65}Al_{0.35}As$ barrier and 42–23 Å GaAs–$Ga_{0.65}Al_{0.35}As$ superlattices doped to 1×10^{18} cm^{-3}, as electrodes; (b) current–voltage characteristic at 4.2 K for a double-barrier resonant tunneling diode with 100 Å $Ga_{0.60}Al_{0.40}As$ barriers and a 40 Å GaAs well; (c) Fano factor F ($F = S/2eI$, where S is the noise spectral density and I is the current) for the diode of part (a). The value of F remains around 1, before and after the negative differential conductance region; (d) Fano factor for the double-barrier diode of part (b). In contrast with the result of (c), F falls below 1 below the peak-current voltage and is enhanced well above 1 in the negative differential conductance region. The double traces that appear in (c) and (d) correspond to measurements taken by sweeping the voltage up and down.

tween the collector minibands blocks the tunneling electrons and (ideally) the current vanishes. At even higher voltages, the current increases again when the collector's second miniband becomes aligned with the emitter's first miniband.[11]

The superlattice tunnel diode was implemented by preparing by molecular beam epitaxy a semiconductor heterostructure with an undoped 102 Å $Ga_{0.65}Al_{0.35}As$ barrier and a 50-period superlattice on each side of the barrier. Each period was a 42–23 Å GaAs–$Ga_{0.65}Al_{0.35}As$ pair, doped uniformly with 1×10^{18} cm^{-3} Si donors in one heterostructure (device A) and 5×10^{16} cm^{-3} in a second, otherwise identical, structure (device B). Two additional heterostructures were prepared as control samples. In one, both electrodes were n^+ GaAs regions (device C) instead of superlattices. The second control sample was a double-barrier diode with 100 Å $Ga_{0.60}Al_{0.40}As$ barriers and a 40 Å GaAs well, and with n-type GaAs electrodes (device D). In all cases, substrate and cap layers were heavily doped n-type GaAs, to which ohmic contacts were made by evaporating and annealing a AuGe–Ni alloy.

The $I-V$ characteristic for device A at $T = 4.2$ K is shown in Fig. 2(a). Initially, the current increases almost linearly with increasing bias between the emitter and collector electrodes. The quasilinear dependence is followed by a current drop at around 25 mV, which continues up to 150 mV, at which point the current increases rapidly with bias. This behavior is consistent with the transport mechanism described above for a superlattice tunnel diode. Sample B (not shown) exhibited a similar characteristic, although the peak-current and valley-current voltages were larger.

For the material parameters of samples A and B, a simple Kronig–Penney calculation of the superlattice yields a 52 meV width for the ground-state miniband.[12] This num-

ber is considerably larger than the 25 meV derived from the peak voltage in Fig. 2(a), although it agrees with the 50 meV obtained from the peak voltage for the opposite bias polarity (not shown). The asymmetry between the two bias directions is probably a consequence of an unintentional difference between the two superlattice electrodes. The larger voltages found for sample B result from light doping at the electrodes, where a significant portion of the applied voltage drops.

Control sample C exhibited a nonlinear $I-V$ characteristic at 4.2 K but, as expected, no sign of NDC. Finally, the double-barrier diode (sample D) had a sharp NDC region at 266 mV [see Fig. 2(b)], corresponding to the voltage at which the confined state in the well passes below the conduction band edge of the emitter.

Once the $I-V$ characteristics of the various structures are well established, we can focus on their noise characteristics at 4.2 K. In all cases, except at the smallest voltages, the noise was proportional to the current, an indication that the typical currents flowing through the devices were large enough to make thermal noise negligible. At the same time, care was taken to restrict the currents (by a combinaton of design of the tunnel barriers and of device size) to low enough levels so that no hysteresis due to external-circuit instability was present in the NDC regions of the $I-V$ characteristics.

Figure 2(c), which shows the Fano factor of sample A as a function of voltage, captures the essence of this work: within experimental uncertainty, F is essentially one in the entire voltage range. As also observed in sample B, there is neither suppression nor enhancement before or after the NDC region. This is in marked contrast with the Fano factor we obtained for the double-barrier diode, sample D, shown in Fig. 2(d). Here F falls significantly below 1 in the quasi-

linear current region and then shoots up sharply up to 2.3 at the NDC voltage, to fall back to 1 once the NDC region disappears.

The sharp difference between the noise characteristics of the two types of NDC devices stems from the difference in their tunneling mechanisms. The partial suppression of shot noise in the linear regime of the double-barrier diode has been explained by the charge correlation imposed by Pauli's exclusion principle, which prevents an electron from tunneling from the emitter into the quantum well unless the confined state is unoccupied. Noise suppression is thus a consequence of charge accumulation in the well.

Theoretically, the Fano factor is $F = 0.5$ when the tunneling probabilities through the individual barriers are the same, and it approaches 1 when they are very different from each other.[8] In the case of Fig. 2(d) the minimum Fano factor is about 0.7 and not 0.5, which implies an asymmetry between the two barriers, either intrinsic or induced by the applied voltage. Still, the noise reduction in the quasilinear regime is unambiguous proof of charge accumulation in the well, which occurs even if intrinsic bistability is not observed in the NDC region.[3]

The noise enhancement in the NDC region of a double-barrier diode has been attributed to electrostatic-potential fluctuations when an electron tunnels into the well. Once the confined state falls below the electrode's conduction-band edge and the tunneling density of states is very small, those fluctuations lead to positive feedback and charge correlations that increase shot noise.[5,6] A self-consistent calculation of the $I-V$ and $S-V$ characteristics using a linear approximation has shown that indeed the Fano factor diverges as the NDC voltage is approached.[7]

In contrast, in the superlattice tunnel diode of Fig. 1 there is no tunnel bottleneck and no charge accumulation. Electron tunneling is then an uncorrelated process and, as our results show, shot noise does not deviate from its Poissonian behavior, regardless of whether the diode is in the NDC regime or not. From the point of view of noise, the superlattice tunnel diode is not different from a conventional single-barrier heterostructure such as sample C, for which we found $F = 1$ throughout the voltage range ($V \leqslant 140$ mV).

After comparing experimentally the noise properties of two types of NDC devices, we conclude that charge accumulation, not system instability, is ultimately responsible for the super-Poissonian shot noise of the NDC region. Simple noise measurements like those presented here should be able to discern between competing transport mechanisms in other mesoscopic structures in which charge accumulation is an issue, even as subtle as in the case of tunneling through a single barrier into a quantum well.[13] Such measurements might also help to differentiate between sequential and coherent tunneling in multiple-well heterostructures.

[1] R. Landauer, Nature (London) **392**, 658 (1998).

[2] For a recent review see, e.g., *The Physics and Applications of Resonant Tunneling Diodes*, edited by H. Mizuta and T. Tanoue (Cambridge University Press, Cambridge, 1995).

[3] Y. P. Li, A. Zaslavsky, D. C. Tsui, M. Santos, and M. Shayegan, Phys. Rev. B **41**, 8388 (1990).

[4] E. R. Brown, IEEE Trans. Electron Devices **39**, 2686 (1992).

[5] G. Iannaccone, G. Lombardi, M. Macucci, and B. Pellegrini, Phys. Rev. Lett. **80**, 1054 (1998).

[6] V. V. Kuznetsov, E. E. Mendez, J. D. Bruno, and J. T. Pham, Phys. Rev. B **58**, R10159 (1998).

[7] Ya. M. Blanter and M. Büttiker, Phys. Rev. B **59**, 10217 (1999).

[8] Ya. M. Blanter and M. Büttiker, Phys. Rep. **336**, 1 (2000).

[9] R. Davies, M. Kelly, and T. Kerr, Phys. Rev. Lett. **55**, 1114 (1985).

[10] J. W. Sleight, R. J. Aggarwal, W. Duncan, Y.-C. Kao, H. L. Tsai, W. R. Frensley, C. L. Fernando, and M. A. Reed, Phys. Rev. B **51**, 10701 (1995).

[11] The mechanism that gives rise to NDC in a superlattice tunnel diode is analogous to that of a conventional tunnel (Esaki) diode, whose noise properties were studied long ago [J. J. Tiemann, Proc. IRE **48**, 1418 (1960)]. Unfortunately, those early experiments were done at room temperature and using a very primitive (for today's standards) noise-measurement setup, so that the results were not conclusive. The data showed that the noise's power spectral density was somewhat larger than $2eI$ at the beginning of the NDC region. This behavior was accounted for by a model that assumed full shot noise and included the contribution of both the emitter-to-collector and collector-to-emitter currents.

[12] The following values were used: barrier height, 310 meV; effective mass, 0.067 m_0, where m_0 is the free-electron mass.

[13] H. Morkoç, J. Chen, U. K. Reddy, T. Henderson, and S. Luryi, Appl. Phys. Lett. **49**, 70 (1986).